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## Thermal analysis of bending under tension test

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### Abstract

The tribological conditions in deep drawing can be simulated in the Bending Under Tension test to evaluate the performance of new lubricants, tool materials, etc. Deep drawing production with automatic handling runs normally at high rate. This implies considerable heating of the tools, which sometimes can cause lubricant film breakdown and galling. In order to replicate the production conditions in bending under tension testing it is thus important to control the tool/workpiece interface temperature. This can be done by pre-heating the tool, but it is essential that the interface temperature during testing is similar to the one in the production tool. A universal sheet tribo-tester has been developed, which can run multiple tests automatically from coil. This allows emulating the temperature increase as in production. The present work performs finite element analysis of the evolution and distribution of temperature in the bending under tension test by making use of boundary conditions and calibration values directly measured from experiments. The overall methodology combines 2D and 3D models of the bending under tension test with steady state and transient thermal and thermo-mechanical procedures. Results show that the proposed methodology applied to a single stroke can effectively and accurately predict the interface temperature in the test tool, thus avoiding the otherwise required thousands of thermo-mechanical FEM analyses of temperature development during testing before thermal steady state has been reached.

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## 1. Introduction

The introduction of new materials in sheet metal forming, e.g. advanced high strength steels, lean duplex steels, and titanium alloys has implied severe tribological conditions in form of high normal pressures and temperatures at the tool/workpiece interface. In critical cases these parameter values become too high, which leads to metal-to-metal contact, pick-up and galling. Production in progressive tools with increasing production rates add further to the problem of high temperatures, and policies against the use of environmentally hazardous lubricants e.g. chlorinated paraffin oils makes it still more critical to ensure sound production without lubricant film breakdown and galling, Bay et al. (2010).

Since testing of new lubricants in production tools is costly and problematic, simulative testing in the laboratory are favored, and as regards sheet metal forming a variety of tests have been developed, Bay et al. (2008). Concerning deep drawing and redrawing, which are the processes related to the present investigation, the bending under tension test is appropriate. A description of this test, which is applied in the present investigation, is given by Andreassen et al. (2006).

The present work is focused on determination of the temperature distribution in the tool and the tool/workpiece interface in bending under tension testing proposing a new, combined numerical and experimental approach. Experimentation makes use of a newly built universal sheet tribo-tester, where the test is carried out directly from coil in order to reproduce real production conditions, Ceron and Bay (2013). Numerical modelling is based upon a new approach that only requires modelling of a single stroke of the bending under tension test to obtain the necessary data for the temperature calculation. This is accomplished by employing thermal boundary conditions retrieved from measuring the temperature in a few, selected points in the test after performing the required number of strokes to obtain thermal steady state conditions. The proposed approach falls into what one may consider a combined numerical-experimental procedure, not in the sense of experiments being used to validate numerical estimates, but in the sense that experiments provide the boundary conditions for running the finite element numerical simulations.

## 2. Experimental setup

The bending under tension test was performed to simulate a concrete industrial production of a Ø18x20 mm cup made by deep drawing followed by two redrawings in a progressive tool, Fig. 1. The workpiece material is a 1 mm strip of advanced high strength steel Docol® DP 800 from SSAB, the tool material is PM tool steel Vanadis® 4E from Uddeholm, and the lubricant is Anticorit PLS 100 T from Fuchs Europe. The tribological conditions, which are most severe in the second redrawing operation, marked 3 in Fig. 1, were simulated with the bending under tension test. A numerical analysis of the production process showed that the normal pressure at the contact interface between workpiece and die in this operation is extremely high with peak values of app. 1600 MPa.

The test tool is a rectangular pin with 10x10 mm cross section pin, where the four edges with radius 3.5 mm corresponding to the die radius in the production tool are the working surfaces, see Fig. 2. In order to reproduce the high pressure reached in production, the test tool geometry was designed, so that the possible contact was limited to 45° as shown in Fig. 2. The back tension was set to 300 MPa in order to achieve a normal pressure of about 1600 MPa. The bending under tension tests were performed with the same tribo-system as in production on a recently built Universal Sheet Tribotester, which can run automatically from coil. The tribotester has two axes: the primary axis moves horizontally forth and back and pulls the strip during the test. The maximum sliding length is 500 mm. The secondary axis moves up and down and applies a constant back tension to the strip. The maximum sliding length is 250 mm. In the present tests a sliding length of 20 mm was set corresponding to second redrawing in the production process. The test was repeated 1500 times, every stroke with a new, virgin workpiece surface. The tool surface was kept the same. The sliding speed was 50 mm/s, whereas the idle time between two consecutive strokes was set to 0.8 s, thereby obtaining a test rate of 40 strokes/min, which is equal to the current production rate. A thermocouple type K was welded inside the test tool at 2 mm distance from the contact surface, at the red dot in Fig. 2 right. The temperature was acquired throughout the test with a sample rate of 13 Hz.

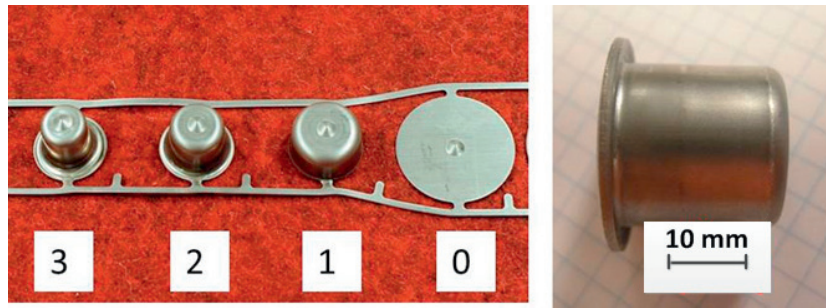


Fig. 1. Sequence of operation in the progressive tool (left) and final cup (right).

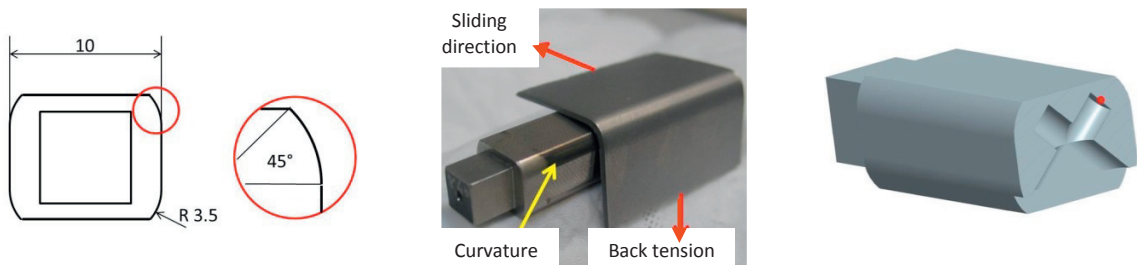


Fig. 2. Cross sections of the BUT tool with detailed view of curvature (left), photo of tool and strip (middle) and schematic of holes for mounting thermocouple (right).

### 3. Numerical model

The temperature evolution of the tool pin was analyzed by means of LSDYNA<sup>®</sup>. A 2D model was developed, which is shown in Fig. 3. The model includes a 50 mm long strip, the tool pin and the tool holder. Plane strain condition is assumed, since the strip has a width of 30 mm, while the thickness is 1 mm. Fig. 3b shows a detail of the contact interface between workpiece and tool pin. The red dot indicates where the thermocouple is welded in the real tool. Fig. 4 shows the temperature development measured in the experiments. Three major trends are noticed:

- temperature increases with the number of strokes due to thermal energy accumulation in the tool (Fig. 4a)
- temperature increases in each single stroke due to deformation and friction energy (Fig. 4b)
- temperature decreases during repositioning of axes to home position (Fig. 4c)

The first trend is the logical consequence of thermal conduction from the contact interface through the die. Fig. 4a shows the temperature evolution within 1500 strokes, after which an average of 68°C is reached at the measuring point 2 mm below the contact interface. Steady state is almost reached. Fig. 4b shows the temperature development in a single stroke. The strip moves 20 mm at a speed of 50 mm/s in about 0.5 s generating thermal energy, which raises the temperature. After this the strip remains still during the idle time, which is 0.8 sec. During this period the heat is dissipated to the environment and the tool holder. As seen in Fig. 4b the temperature raises from 60.5 to 64°C in a single stroke. The third trend is fairly critical because it reduces the steady state temperature

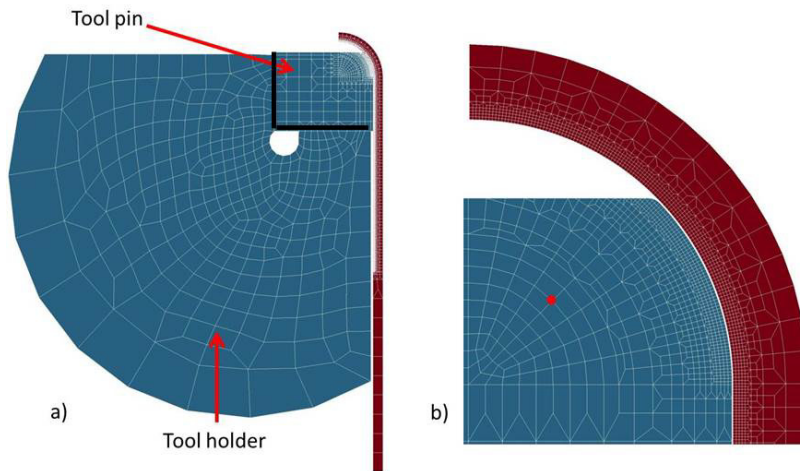


Fig. 3. (a) Two-dimensional finite element model of bending under tension test, (b) detail showing tool curvature. The red dot indicates correspondent position of the thermocouple in the real tool.

of the tool. Although the axes move back at a maximum speed of 150 mm/s, it still takes approximately 10 s before the next stroke starts. In the present case, with a 20 mm sliding length, it was possible to perform about 12-13 strokes between two homing operations. Fig. 4c shows the drop in temperature from 64 to about 55°C during repositioning of the axes.

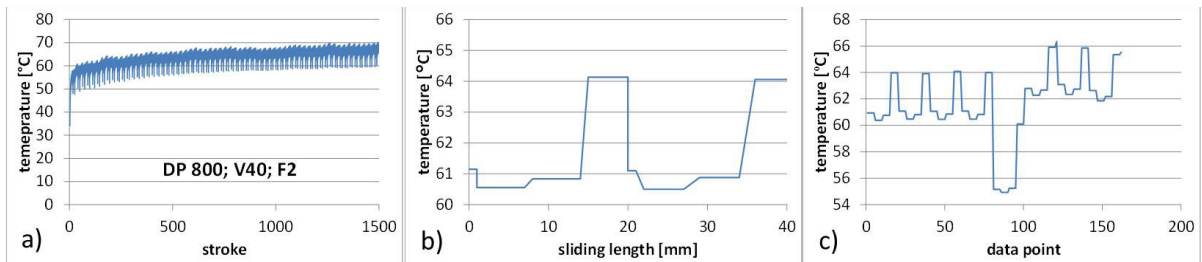


Fig. 4. Experimental evolution of temperature (a) with stroke number during the bending under tension test, (b) with sliding length during two strokes and (c) with data points (time) during repositioning of axis 1 and 2.

The distribution of temperature was calculated by means of a combined numerical-experimental approach that eliminates the need to perform a long and complex non-linear modelling of the bending under tension test over at least 1000 strokes in order to attain steady-state operating conditions. Instead, only a single stroke was necessary to simulate. This was carried out by a sequence of numerical procedures involving a two-dimensional steady-state thermal analysis with boundary conditions retrieved from experimental measurements after 1000 strokes. The measurements were 61°C at the thermocouple position and 41°C at the curved peripheral surface of the tool holder shown in Fig. 3a.

The calculated steady-state thermal conditions of the tool were subsequently uploaded into a thermo-mechanical model in order to determine the influence of heat transfer on the overall temperature distribution resulting from plastic deformation and friction under the non-steady state operative conditions resulting from ~~after a~~ bending under tension testing with sliding length 20 mm. Both models were performed in 2D.

The drawback of using a 2D model to determine the temperature distribution during homing operations is that thermal dissipation through the third dimension (axis of the pin tool) and the hole, where the thermocouple is inserted, are not taken into consideration. This was the reason why a final 3D non-steady state finite element thermal analysis was necessary to determine the overall heating and cooling cycle of the tool pin. Only half length

of the tool pin was modelled considering the thermal flux to be symmetric with respect to the symmetry plane of the tool. The resulting finite element model consists of 270,000 linear tetrahedral elements, but it runs in just a few minutes instead of many hours as would be necessary if a full non-steady state, thermo-mechanical model had been used throughout the 1000 steps of testing. The initial temperature of each node is calculated similarly to the way it was done for the 2D model. The only difference is that the tool holder is disregarded in the 3D model, and the two boundary conditions are the temperature of the thermocouple and the temperature along the tool pin contact with the (removed) tool holder. The latter is retrieved from the 2D simulation results. At this point the temperature at the contact interface between tool and workpiece can be simulated even without having the strip in the model. To do this, the temperature of the nodes, as a function of time, at the contact interface are taken from the coupled 2D model and applied to the nodes, which are supposed to be in contact with the strip in the 3D model.

To simulate the temperature decrease during repositioning, the 3D model is used again. The initial conditions of this model are the temperature in the nodes at the end of the previous simulation. The model is run for 10 s, where thermal energy is not generated but only dissipated towards the environment. The contact with the tool holder is simulated with higher heat transfer coefficient on that part of the tool pin interface, where contact with the tool holder occurs.

#### 4. Results

Fig. 5a shows the temperature field in the tool pin and the tool holder determined in the steady state analysis. As expected the gradient of temperature extends radially inwards from the round peripheral surface of the tool holder, which is the coldest, to the tool pin. This is therefore the initial temperature that is introduced in the model. Fig. 5b shows the results after the strip has moved 20 mm with a back tension of 300 MPa. The strip temperature quickly increases from room temperature to more than 61°C. Experimental measurement reveals that the strip temperature right after bending is about 90°C and a similar value is also found in the numerical model. The peak value in the contact interface is about 85°C, but the overall temperature field in the tool pin does not change significantly compared with the initial condition, since the heat generated by a single 20 mm test lasting 0.5 s is fairly small. The coefficient of friction was calibrated towards the measured drawing force, whereas the heat transfer coefficient was calibrated using the temperature measured by the thermocouple. The conductivity and specific heat capacity were given by the tool and workpiece material suppliers.

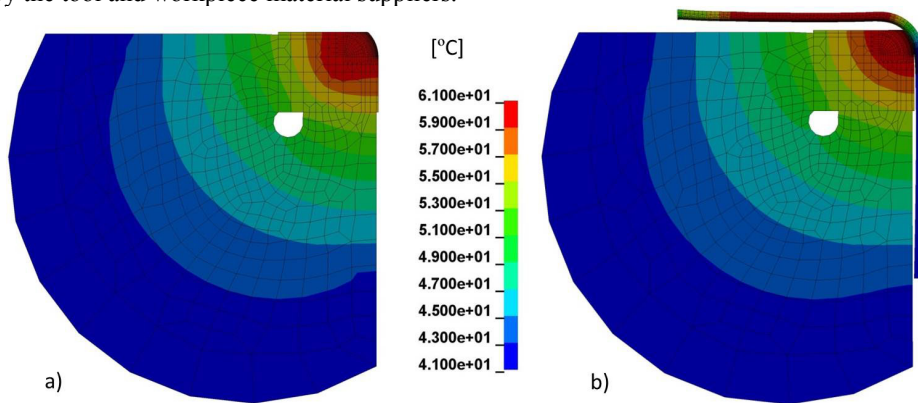


Fig. 5. (a) Temperature field in bending under tension tool (a) at steady state just before testing; (b) just after testing.

Fig. 6a shows the temperature development, at the thermocouple position, calculated in the 3D model. The curve includes an initial increase due to heat development by deformation and friction, after which the temperature decreases approximately 10°C due to heat dissipation to the surroundings. The size of the temperature drop is similar to what is measured in the experiments. Fig. 6b shows the temperature field after repositioning of the axes.



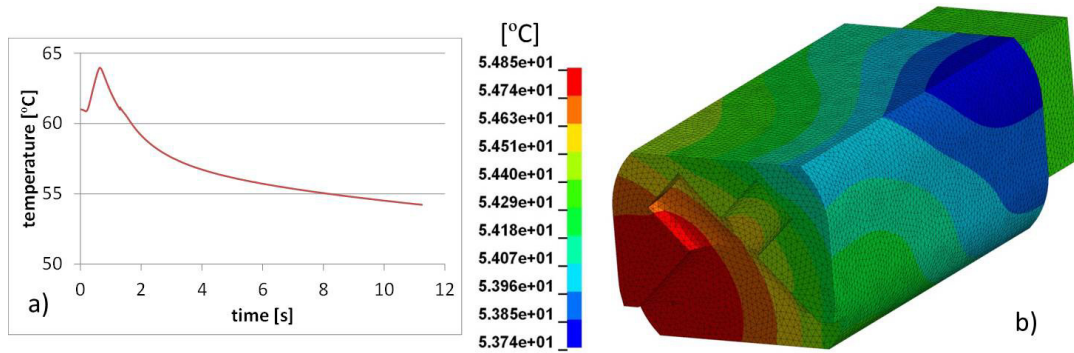


Fig. 6. (a) Temperature development at thermocouple position; (b) temperature field after repositioning of two axes.

The reader should notice the small temperature range (53.74–54.85°C), which indicates that the heat flows radially towards the tool holder. Moreover it is noticed that tool pin has a fairly homogeneous temperature of 54°C.

## 5. Conclusion

When testing performance of new tribo-systems for sheet forming operations with simulative laboratory tests it is vital to ensure the same values of main tribo-parameters, e.g. normal pressure, sliding length, sliding velocity and tool/workpiece interface temperature. The present paper shows, how the bending under tension test can be designed and analysed to ensure good control of the tribo-parameters, especially as regards the temperature by using a newly built sheet-tribo-tester, which runs multiple tests automatically from coil, and combining with numerical modelling by means of the finite element method.

Numerical modelling was performed by means of a new, combined numerical-experimental approach that uses the experimental measurements of a temperature in a few points of the tool at thermal steady state to define appropriate boundary-conditions in the subsequent thermo-mechanical analysis of the test under 2D plane strain assumptions. Results show that the peak temperature in the tool/workpiece interface is approximately equal to 85°C. The decrease of temperature during the repositioning of the axes of the tribo-tester is also modelled by means of a non-steady state 3D thermal analysis that accounts for all the geometric details of the pin tool and for heat dissipation along its axis. Results show that the temperature of the tool pin decreases during repositioning of the axis down to a value equal to 54°C. The overall procedure allows modelling the distribution of temperature resulting from the 1000 strokes corresponding to the experimental steady-state regime of the bending under tension tests in a single test stroke.

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